

## Axial Vector Tetraquark with Two s-quarks

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Possibility of an axial vector isoscalar tetraquark  $ud\bar{s}\bar{s}$  is discussed. If a  $f_1$  meson in the mass region  $1.4 - 1.5$  GeV consists of four quarks  $ns\bar{n}\bar{s}$ , the mass of the isoscalar  $ud\bar{s}\bar{s}(\vartheta^+$ -meson) state with  $J^P = 1^+$  is expected to be lower than that of the  $f_1$  meson. Within a flux-tube quark model, a possible resonant state of  $ud\bar{s}\bar{s}(J^P = 1^+)$  is suggested to appear at  $\sim 1.4$  GeV with the width  $\mathcal{O}(20 \sim 50)$  MeV. We propose that the  $\vartheta^+$ -meson is the good candidate for the tetraquark search, which would be observed in the  $K^+K^+\pi^-$  decay channel.

The possibility of multiquark states has been discussed for a long time.<sup>1)–10)</sup> In particular, the possible  $qq\bar{q}\bar{q}$  states have been suggested in many theoretical efforts to understand light scalar mesons(for example, Refs.[1,3,11]). The  $4q$  states were proposed in the description of  $f_0(600)$  and  $f_0(980)$ , where the strong attraction between  $(qq)_3$  and  $(\bar{q}\bar{q})_3$  play an important role.<sup>1),11)</sup> Here,  $(qq)_3$  and  $(\bar{q}\bar{q})_3$  denote the color-anti-triplet quark pair and the color-triplet anti-quark pair, respectively. On the other hand, the  $KK$  molecule states were suggested to understand the properties of  $f_0(980)$  and  $a_0(980)$ .<sup>3)</sup> Even if the  $4q$  components are dominant in a certain meson with the conventional flavor, it is difficult to find a direct evidence of the  $4q$  components due to the mixing with the conventional  $q\bar{q}$  state via the annihilation of  $q\bar{q}$  pairs. Our main interest here is the possibility of “tetraquark” states which has the minimal 4-quark content.

The recent observation of  $D_{sJ}(2317)$ <sup>12)</sup> and the reports of the pentaquark baryon  $\Theta^+(uudd\bar{s})$ ,<sup>13)</sup> revived the motivation of the experimental and theoretical researches on multiquarks in hadron physics, though the existence of  $\Theta^+$  yet to be well established. One of the striking characteristics of the  $\Theta^+$  is its narrow width. For the theoretical interpretation of the narrow  $\Theta^+$  state, the possibility of the spin-parity  $J^P = 1/2^+$  and  $J^P = 3/2^-$  have been discussed by many groups.<sup>10),14)–19)</sup> The unnatural spin and parity is a key of the suppressed width for the lowest decay channel.

Now we turn to the discussion on the possibility of the tetraquarks. If we accept the interpretation of the pentaquark as the  $(ud)_3(ud)_3\bar{q}$  state based on the diquark picture by Jaffe and Wilczek, it is natural to expect that a tetraquark with the  $ud\bar{s}\bar{s}$  content may exist at the nearly same energy region by replacing a  $ud$ -diquark with  $\bar{s}$  quark. Firstly, one should consider the states with unnatural spin and parity, which

cannot decay into two light hadrons (pseudo scalar mesons) in the  $S$ -wave channel. Second, the exotic color configurations  $(qq)_3(\bar{q}\bar{q})_3$  would be essential to stabilize the exotic hadrons. Then, we propose a  $J^P = 1^+ ud\bar{s}\bar{s}$  state with the  $(qq)_3(\bar{q}\bar{q})_3$  configuration as the candidate of narrow tetraquark states. It should be stressed that two-body  $KK$  decays from any  $J^P = 1^+ ud\bar{s}\bar{s}$  state are forbidden because of the conservation of the total spin and parity. The lowest threshold energy of the allowed two-body decays is 1.39 GeV for the  $KK^*(895)$  channel. If the mass of the  $J^P = 1^+ ud\bar{s}\bar{s}$  state lies below(closely to) the  $KK^*$ , two-meson decay channels are (almost) closed, and hence, its width must be narrow.

The tetraquark  $ud\bar{s}\bar{s}$  states were discussed in Ref.[1], and noted as  $E_{(KK)}$ -mesons. In the MIT bag model,<sup>1)</sup> the theoretical mass for the isoscalar  $ud\bar{s}\bar{s}(J^P = 1^+)$  state was predicted to be 1.65 GeV. Recently the isoscalar  $ud\bar{s}\bar{s}$  state with  $J^P = 1^-$  was suggested in analogy with the  $\Theta^+$  by Burns et al.,<sup>20)</sup> and its mass was predicted to be  $\sim 1.6$  GeV. The isoscalar tetraquark  $ud\bar{s}\bar{s}$  in the flavor  $\bar{10}$  group was called  $\vartheta^+$ -meson in Ref.[20] in the association with the  $\Theta$  baryon. In this paper, we investigate the  $\vartheta^+$ -meson( $J^P = 1^+$ ) with a constituent quark model. The theoretical method of the calculations is the same as that applied to the study of pentaquark and tetraquark in Refs.[17,21]. Namely, we apply the flux-tube quark model with antisymmetrized molecular dynamics(AMD)<sup>22)</sup> to  $4q$  systems. Based on the picture of a flux-tube model, we ignore the coupling between the configurations  $(qq)_3(\bar{q}\bar{q})_3$  and  $(q\bar{q})_1(q\bar{q})_1$ , and solve the  $4q$  dynamics with the variational method only in the model space within the exotic color configuration  $(qq)_3(\bar{q}\bar{q})_3$ . By assuming that the  $f_1$  meson in the 1.4~1.5 GeV mass region as the  $4q$  state, we predict the mass and the width of the tetraquark  $\vartheta^+(J^P = 1^+)$ .

The method of AMD is a variational method. The adopted Hamiltonian is the same as that of previous works.<sup>17),21)</sup> The Coulomb and color-magnetic terms of the OGE potential and the string potential are taken into account. The parameters in the Hamiltonian are chosen to reasonably reproduce the normal hadron spectra.<sup>21)</sup> In order to evaluate the  $\vartheta^+(1^+)$  mass and the width, we adopt the observed data of the  $f_1$ -mesons( $f_1(1420)$  and  $f_1(1510)$ ) in the 1.4~1.5 GeV region as an input. The details of the formulations for fourquark systems are explained in Ref.[21].

As mentioned in,<sup>21)</sup> in order to predict the  $\vartheta$ -meson mass, we need to determine the mass shift parameter  $M_0$  in the string potential for fourquark  $(qq)_3(\bar{q}\bar{q})_3$  systems. Here, we use the  $f_1$ -meson mass as the input to determine the mass shift. In the mass region 1~1.6 GeV, three  $f_1$ -mesons,  $f_1(1285)$ ,  $f_1(1420)$ , and  $f_1(1510)$  are known, though the  $f_1(1510)$  is not well established.<sup>23)</sup> In the  $P$ -wave  $q\bar{q}$  state, two  $f_1$ -mesons are expected to appear in this energy region as the partners of the  $q\bar{q}$  nonet. It is considered that the lower one is dominated by the light-quark  $u\bar{u}$  and  $d\bar{d}$  components( $n\bar{n}$ ), and the major component of the higher one is the  $s\bar{s}$  state. In the general interpretation, the lowest  $f_1$ -meson( $f_1(1285)$ ) is regarded as the  $n\bar{n}$  state. However, there are two candidates ( $f_1(1420)$  and  $f_1(1510)$ ) for the  $q\bar{q}$  partner of the  $f_1(1285)$ , and the assignment is not confirmed yet. In the constituent quark model calculation,<sup>24)</sup> the masses of the two  $1^{++} q\bar{q}$  states in the  $P$ -wave  $q\bar{q}$  nonet are 1.24 and 1.48 GeV. The theoretical mass spectra of the  $1^{++} q\bar{q}$  states seems to be

consistent with the experimental ones if  $f_1(1510)$  is assigned to be the partner of the  $f_1(1285)$  in the flavor nonet. This is consistent with the assignment in Ref.[25]. On the other hand, an alternative interpretation of the  $f_1(1285)$  and  $f_1(1420)$  being the  $q\bar{q}$  partners is claimed in Refs.[23,26,27]. These interpretations lead to an indication that one of the  $f_1(1420)$  or  $f_1(1510)$  may be a non- $q\bar{q}$  meson while the other and  $f_1(1285)$  can be understood as the partners of the conventional  $P$ -wave  $q\bar{q}$  states.

By ignoring the  $q\bar{q}$  annihilation, we calculate the mass of the  $J^{PC}=1^{++} (us)_3(\bar{u}\bar{s})_3$  state for the  $f_1$ -meson with the present framework in the same way as for the tetraquark  $\vartheta$ -meson. We adjust the mass shift parameter  $M_0$  by fitting the mass of the  $f_1(1420)$  or the  $f_1(1510)$ . Then we get the  $\vartheta^+(1^+)$  mass around 1.4 GeV.

The obtained  $\vartheta^+(1^+)$  wave function is dominated by the component with the spin-zero  $(ud)_3$  and the spin-one  $(\bar{s}\bar{s})_3$  in the spatially symmetric configuration,  $(0s)^4$ . This is consistent with the naive expectation in the diquark picture because the spin-zero  $(ud)_3$  gain the color-magnetic interaction while only the spin-one configuration is allowed in the spatially symmetric  $(\bar{s}\bar{s})_3$  pair. As a result of the energy gain of the color magnetic interaction, the  $\vartheta^+(1^+)$  mass is slightly lower than the fourquark  $f_1$  mass.

Next we discuss the width of the  $\vartheta^+(1^+)$  meson. As mentioned above, we suggest that the  $\vartheta^+(1^+)$ -meson may appear in the energy region  $\sim 1.4$  GeV near the  $KK^*$  threshold. The expected decay modes are  $KK^*$  and  $KK\pi$ . If the branching into  $KK^*$  is small enough, the width should be narrow because the phase space for the three-body decays is suppressed in general. In order to discuss the stability of the  $\vartheta^+$ -meson, we consider only the two-hadron decay and give a rough estimation of the  $\vartheta^+$  width assuming that the coupling of the fourquark  $f_1$  with the  $K\bar{K}^*$  and *c.c.* is the same as that of the  $\vartheta^+$  with the  $KK^*$ . By considering the phase space for the two-body decays, we predict the width of  $\vartheta^+(1^+)$  to be  $\Gamma_\vartheta = 20 \sim 50$  MeV.

In summary, we discussed the possibility of the  $J^P = 1^+$  state of the isoscalar tetraquark( $S=+2$ ),  $\vartheta^+$ -meson, with the  $ud\bar{s}\bar{s}$  content. If a  $f_1$  meson in the mass region 1.4–1.5 GeV consists of four quarks  $ns\bar{n}\bar{s}$ , the mass of the isoscalar  $ud\bar{s}\bar{s}$ ( $\vartheta^+$ -meson) state with  $J^P = 1^+$  is expected to be lower than that of the  $f_1$  meson. Within a flux-tube quark model, a possible resonant state of  $ud\bar{s}\bar{s}$ ( $J^P = 1^+$ ) is suggested to appear at  $\sim 1.4$  GeV with the width  $\mathcal{O}(20 \sim 50)$  MeV. We propose that the  $\vartheta^+$ -meson is the good candidate for the tetraquark search, which would be observed in the  $K^+K^+\pi^-$  decay channel.

Recently, the  $\theta^+(1^-)$  and the  $\theta^+(0^+)$  were predicted by Burns et al.<sup>20)</sup> and by Karlier and Lipkin,<sup>28)</sup> respectively. It should be pointed out that the allowed decay channels are different among these three predictions  $J^P = 1^+, 1^-,$  and  $0^+$  states of the  $\vartheta^+$ -mesons. The  $K^+K^+\pi^-$  decay from the  $\vartheta(J^P = 1^+)$  predicted in the present work is suitable for the experimental tetraquark search.

As for the other candidates of the  $4q$  states, it has been theoretically suggested that the scalar mesons like  $f_0(600)$ ,  $f_0(980)$  and  $a_0(980)$  below 1 GeV might be interpreted as  $4q$  states. We calculated the corresponding fourquarks with the present framework. Then, we found that the masses of fourquarks with the exotic color configurations  $(qq)_3(\bar{q}\bar{q})_3$  are much higher than these light scalar mesons. It indicates that these scalar mesons might be other than the dominant  $(qq)_3(\bar{q}\bar{q})_3$  state, but

might be the hybrids of  $P$ -wave  $q\bar{q}$  and fourquark components with meson-meson tails in the outer region as argued in Ref.[27].

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